Preprint
UCRL-JC-145326

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This article was submitted to
46th Annual Meeting International Symposium on Optical Science and Technology, San Diego, CA, July 31-August 5, 2001

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

September 5, 2001

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This work was performed under the auspices of the United States Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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Horizontal Path Laser Communications Employing MEMS Adaptive Optics Correction

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ABSTRACT

Horizontal path laser communications are beginning to provide attractive alternatives for high-speed optical communications. In particular, companies are beginning to sell fiberless alternatives for intranet and sporting event video. These applications are primarily aimed at short distance applications (on the order of 1 km pathlength). There exists a potential need to extend this pathlength to distances much greater than a 1km. For cases of long distance optical propagation, atmospheric turbulence will ultimately limit the maximum achievable data rate. In this paper, we propose a method of improved signal quality through the use of adaptive optics. In particular, we show work in progress toward a high-speed, small footprint Adaptive Optics system for horizontal path laser communications. Such a system relies heavily on recent progress in Micro-Electro-Mechanical Systems (MEMS) deformable mirrors as well as improved communication and computational components. In this paper we detail two Adaptive Optics approaches for improved through-put, the first is the compensated receiver (the traditional Adaptive Optics approach), the second is the compensated transmitter / receiver. The second approach allows for correction of the optical wavefront before transmission from the transmitter and prior to detection at the receiver.

Keywords: Adaptive Optics, Optical Communications, Laser Communications, Free Space Optical Propagation, Free Space Laser Communications, Horizontal Path Communications, Horizontal Path Optical Communications, Horizontal Path Laser Communications

1. INTRODUCTION

Free space optical communications systems are gaining recent popularity due to the desire to solve the "last mile" problem. These systems are showing great promise for high bandwidth connections with minimal infrastructure. Essentially, free space communications can give equivalent performance to fiber-based systems with minimal setup requirements. This makes free space communications ideal for environments that could benefit from quick setup and take downs, for instance, transmission of internet and/or television data at large events (such as for the Olympics or for the SuperBowl). There also exists the desire to send communications within an urban environment (such as a corporate intranet) where it is impractical to lay fiber optic cables. A potentially viable alternative is to use free space laser communications. Companies such as Lucent/Terabeam, Nortel/AirFiber, AstroTerra, Canon, and Hamamatsu have commercial products available to address this need[1,2].

We believe an application space exists for free space optical communications over distances substantially longer than the "last mile". These include both military and civilian applications that require rapidly deployable portable communications infrastructures for battlefield and disaster relief, where transport of large data volumes may be required. For example, communications in support of tele-medicine and tele-maintenance operations As the desire to extend beyond the "last mile" becomes a reality, free space communications systems will be plagued by the effects of the atmosphere; see [3-7]. In particular, turbulence will create a scintillated beam at the receiver. This scintillation will ultimately degrade the overall performance of the system. In this paper, we explore the use of MEMS adaptive optics to correct for the turbulence experienced in free space propagation. The use of adaptive optics systems based on MEMS will, in principle, allow us to extend free space communications distances, improve performance (from a Bit Error Rate, BER, standpoint), and the reduce the overall transceiver size and power requirements.

Traditionally, adaptive optics systems have been quite bulky and did not lend themselves to field-able applications. With new technology in Micro-Electro-Mechanical Systems (MEMS) Spatial Light Modulators, as well as, smaller and faster computers, we are on the verge of creating a high speed Adaptive Optics (AO) systems utilizing minimal space. This makes AO a practical solution for quick and easily field-able applications.

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2. CONCEPT

Our first strategy is to correct using a typical AO approach (ie. correct phase prior to detection). In such a system, the wavefront of the incoming beam is corrected prior to focus onto the electronic sensor (photodiode, APD, etc.). We anticipate improved system performance utilizing this method of correction, however, scintillation will ultimately limit system performance as optical pathlength grows. Although we believe sophisticated algorithms will help improve the system performance in a highly scintillated beam, we would like to propose an additional Adaptive Optics Strategy.

The second strategy we are investigating employs a compensated receiver and transmitter. In this approach, a pair of coupled transmitter / receiver systems (call them device 1 and device 2) are set to communicate exclusively with each other (at least for a finite amount of time). In this system, device 1 (D1), initiates communications with device 2 (D2), separated by a significant atmospheric path. Upon receipt of this optical signal, D2 employs its AO system to minimize the wavefront aberration (and presumably improve detected power). Since D2 has now compensated for the atmospheric path, a transmitted

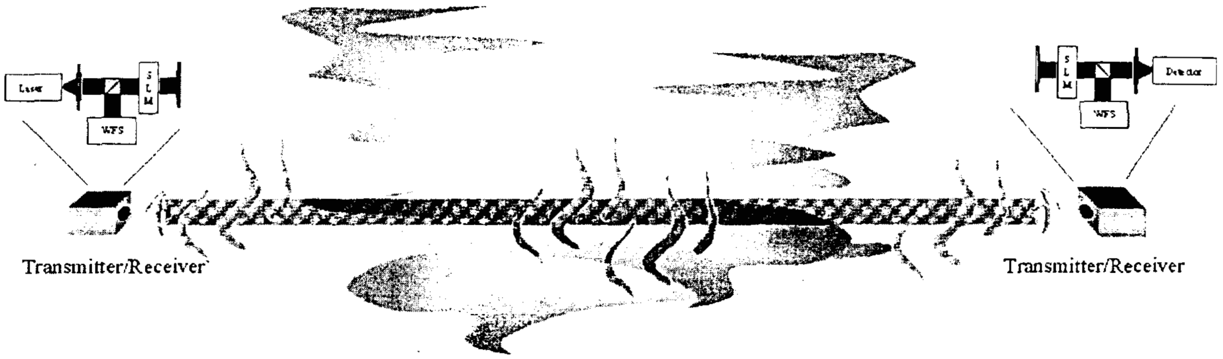

Figure 1. Stylized diagram of horizontal-path optical communications through a turbulent atmosphere.

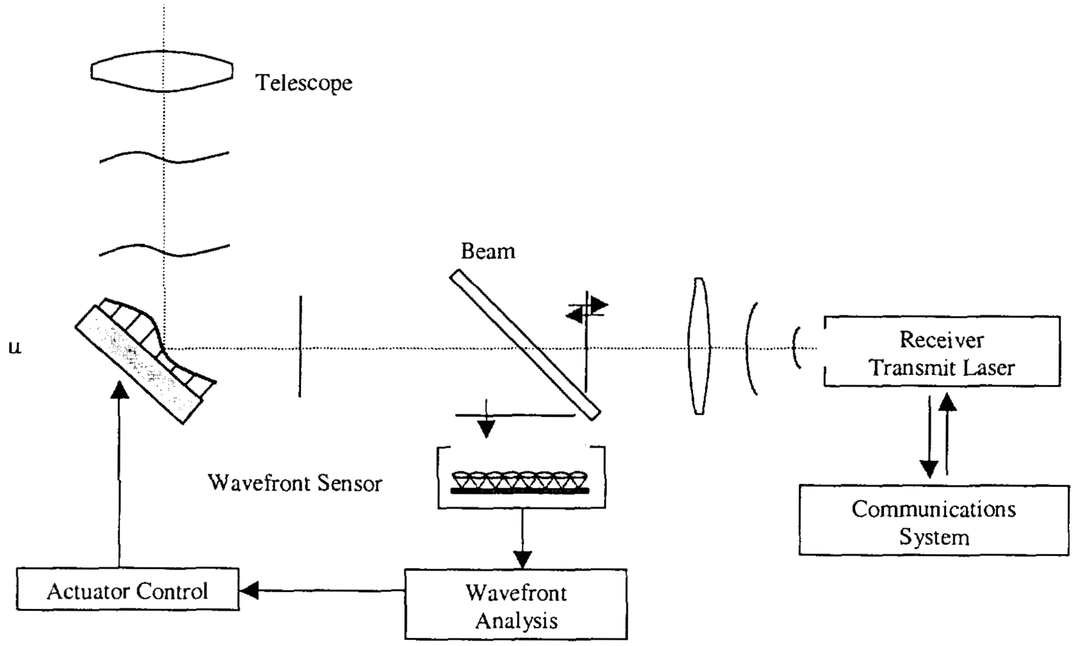

Figure 2. Schematic diagram detailing the operation of the envisioned Adaptive Optics system for use in a laser communications device. Note that the transmit laser and receiver detector share a common optical path (including the deformable mirror).

signal sent from D2 back to D1 can be predistorted before propagating. If the transmitted signal from D2 is within 1 ms (or so) of receipt at D2, it is assumed that the atmospheric path sampled is identical to the received beam and pre-distortion should achieve better detector performance at D1. This is essentially a phase conjugate approach. At D1, the system will then utilize the AO system to further improve the signal on the detector. This "boot strap" type approach is thought to eventually converge on compensated free-space transmitter/receiver system.

It should be noted that once D1 receives the predistorted beam, re-transmission utilizing the set AO system will not necessarily sample the same path, due to D2 predistorting the beam before transmission. For this case, we believe some mirror information would need transmitted from the transmitter to receiver detailing the predistortion the wavefront experienced.

3. SIMULATION

We have employed a simulation strategy to evaluate the effectiveness of our adaptive optical system on the quality of a communication signal. This allows us the opportunity to evaluate the effectiveness of a chosen AO system prior to actual fielding.

We have chosen to concentrate initial simulations on horizontal path propagation, presumably the worst case scenario. Our simulation strategy uses a multi-phase screen approach to model atmospheric disturbances. In short, we employ a Fourier propagation methodology with Kolmogorov phase screens placed throughout the medium. The basic idea is to phase modulate the beam, Fourier propagate a given distance, phase modulate, etc. See, for example, [8-10].

We have chosen to limit our simulations, at this time, to the two basic Adaptive Optics strategies presented above. The first concept employs the AO system to correct the received signal (the traditional AO approach). The second strategy is the same compensated receiver coupled to a compensated transmitter. As mentioned previously, in this approach, the received beam is corrected in a conventional fashion. In return, a signal transmitted back out of the system will be predistorted, and presumably, improve the beam received at the other end.

For the simulations shown in this paper, we have assumed a 1.55 μm communication wavelength over a propagation path of 1 km. For these simulations, ten phase screens were placed 100 m apart each having a value of r_0, based on the following equation[11],

$$r_0 = 1.68\left(C_n^2 L k^2\right)^{-3/5},$$

where C_n^2 is the index of refraction structure parameter, L is the path length, and $k = 2\pi/\lambda$, where λ is 1.55 μm. Assuming a fairly heavy turbulence of C_n^2 of $10^{-12}\text{m}^{-2/3}$, the value of r_0 for 100 m is 19.76 mm. In addition, a transverse wind profile of 10 m/sec was assumed (to allow a time series simulation).

In this first of the simulations, Figure 3 shows the intensity distribution incident on the aperture of the receiving telescope (a) and the corresponding focal spot (b). The telescope diameter assumed in these calculations was 200 mm with a focal length of 1m (f/5). Superposed on the intensity plot is a circle corresponding to the active area of a photo-detector (approximately 100μm in size, or approximately 5 times the diffraction limit.) In the second of these simulations, an AO correction was assumed using a 128 x 128 segmented actuator deformable mirror. As you can see from Figure 3, the intensity structure at the telescope aperture is equivalent, however, the energy on detector has improved. The temporal characteristics of this time series is displayed Figure 4. In this simulation, the effect of scintillation on the wavefront sensor has been ignored. In an actual Shack-Hartmann sensor the scintillation would cause local drop-outs and potential closed loop performance problems. Algorithms to account for wavefront sensing under strong scintillation conditions are being explored and are beyond the scope of this paper. Figure 5 shows actual measured Bit Error Rate and Energy on Detector for our communication system. In this experiment, the lasercom link was running at 1Gbit/sec over a 1.3 km atmospheric path with an assumed C_n^2 of 10^{-12} – 10^{-13}.

With our simulation strategy we have modeled the effects of the number of actuator elements of a segmented DM have on the BER for a fixed C_n^2 of 10^{-12}. Shown in Figure 6 is a plot of BER versus Photons / Bit for different deformable mirror strategies. This plot allows for a simple trade study of transmitted power versus correction ability for an AO system.

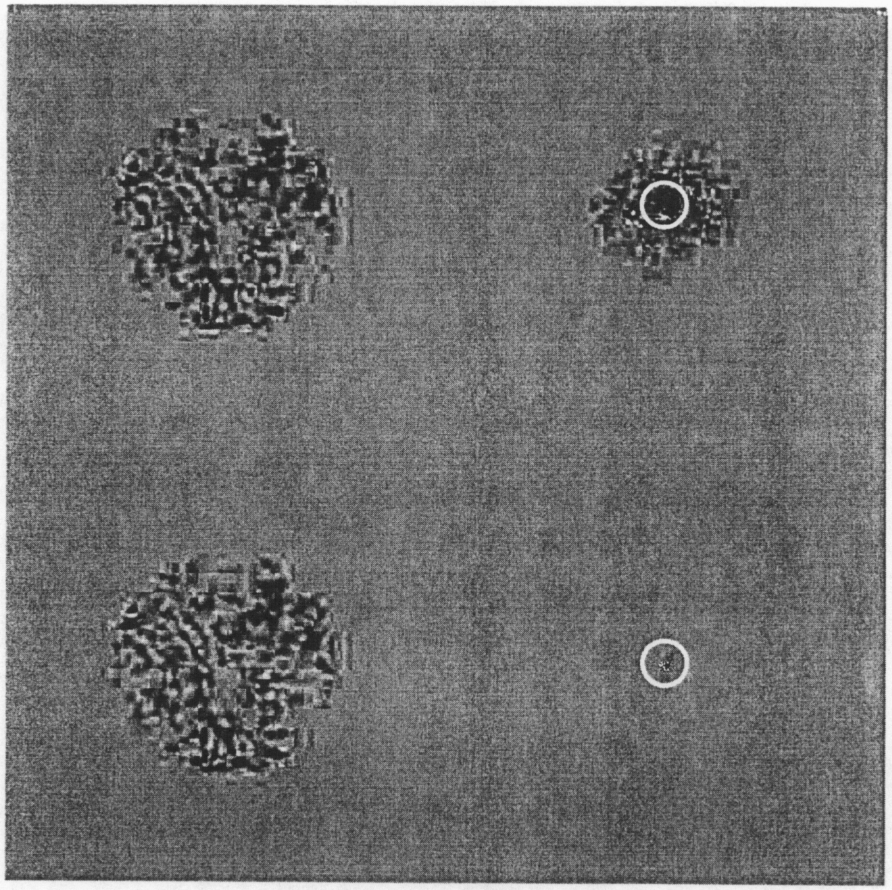

Figure 3. (Top) Simulated intensity at the receiver primary and focal plane / detector (right). (Bottom) Same intensity at the receiver primary, (right) improved focal plane /detector.

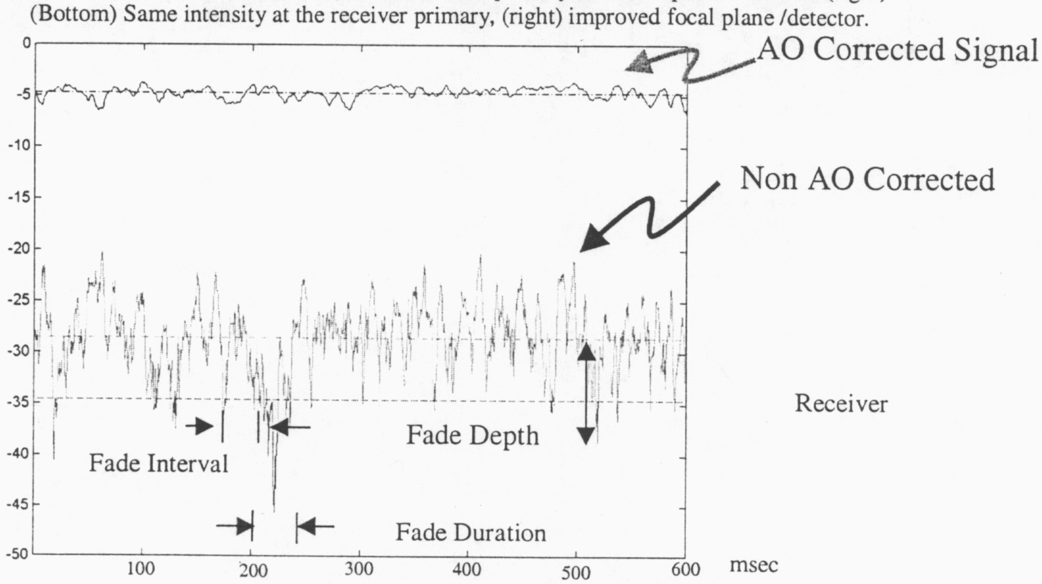

Figure 4. Time series simulation of system performance with and without AO Wind Speed of 10m/s, C_n^2 of $10^{-12}m^{-2/3}$.

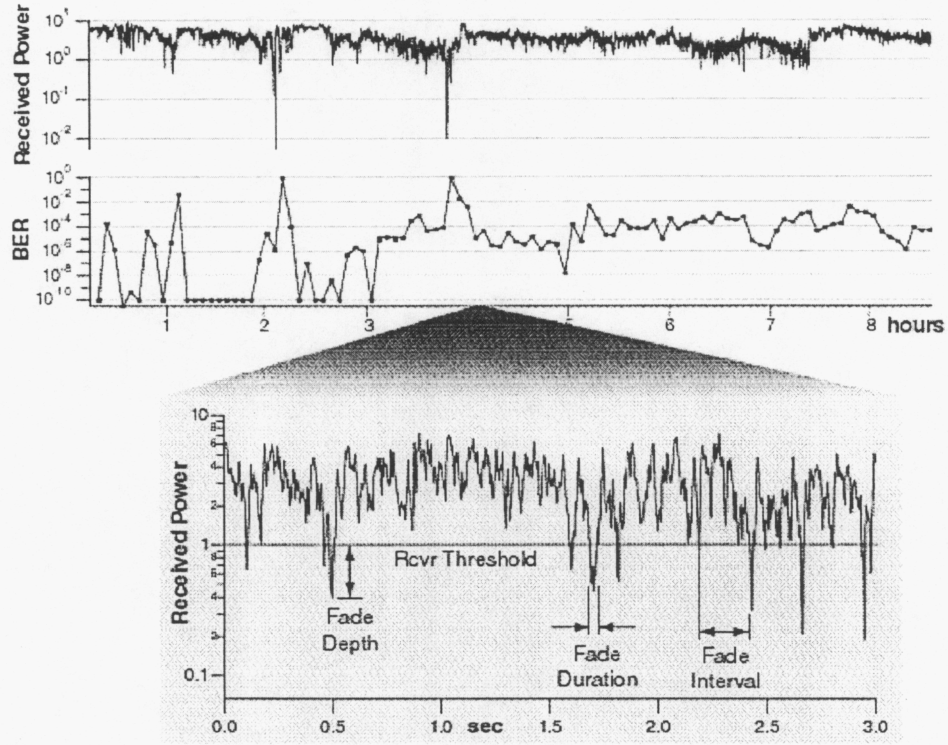

Figure 5. Measured BER of working system.

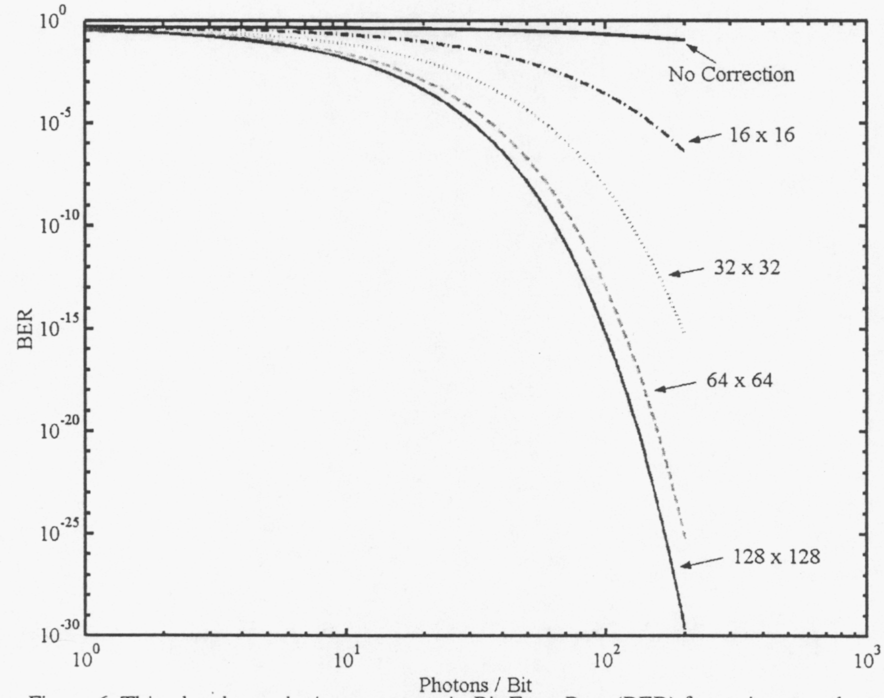

Figure 6. This plot shows the improvement in Bit Error Rate (BER) for various numbers of actuators in an Adaptive Optics system. Plot on the horizontal axis is the number of photons per bit transmitted.

We are currently in the process of simulating the effects of the corrected receiver/transmitter. To reiterate, the idea is to transmit a signal from device 1 to device 2. Upon receipt at device 2, AO correction is performed. Device 2 can then transmit back to device 1 utilizing the correction employed in receipt. This precorrection will, presumably, improve the energy received at device 1.

4. EXPERIMENTATION

We are in the early stages of development of our MEMS Adaptive Optics system. We plan to field the first prototype MEMS based transceiver in early 2002. We are presently operating a 20 Gbit/sec WDM based laser transceiver system testbed over a 1.3 km horizontal path between buildings to characterize the link prior to insertion of the adaptive optics system. We are used data from this system to parameterize the simulations shown in this report. This is shown in Fig. 5.

In the next few months, we plan to implement a high-speed (>1 kHz) wavefront sensor on the 1.3 km testbed. This technology will then be transferred to a 30 km lasercom testbed that is slated for operation in the fall of 2001.

CONCLUSIONS

In this paper, we have presented techniques of AO correction for both a compensated receiver and a compensated transmitter/receiver for use in free space optical communications. Our goal is to develop an easily fieldable AO system to improve performance of long path (much greater than 1 km) optical communications systems. We intend to accomplish this goal by using MEMS micro-mirror arrays, primarily due to their high actuator density and small package size. Also in this paper, we have presented a serious of simulations aimed at studying atmospheric effects on AO performance, prior to system deployment. Upon system deployment, we will validate these simulations, for use in future system designs.

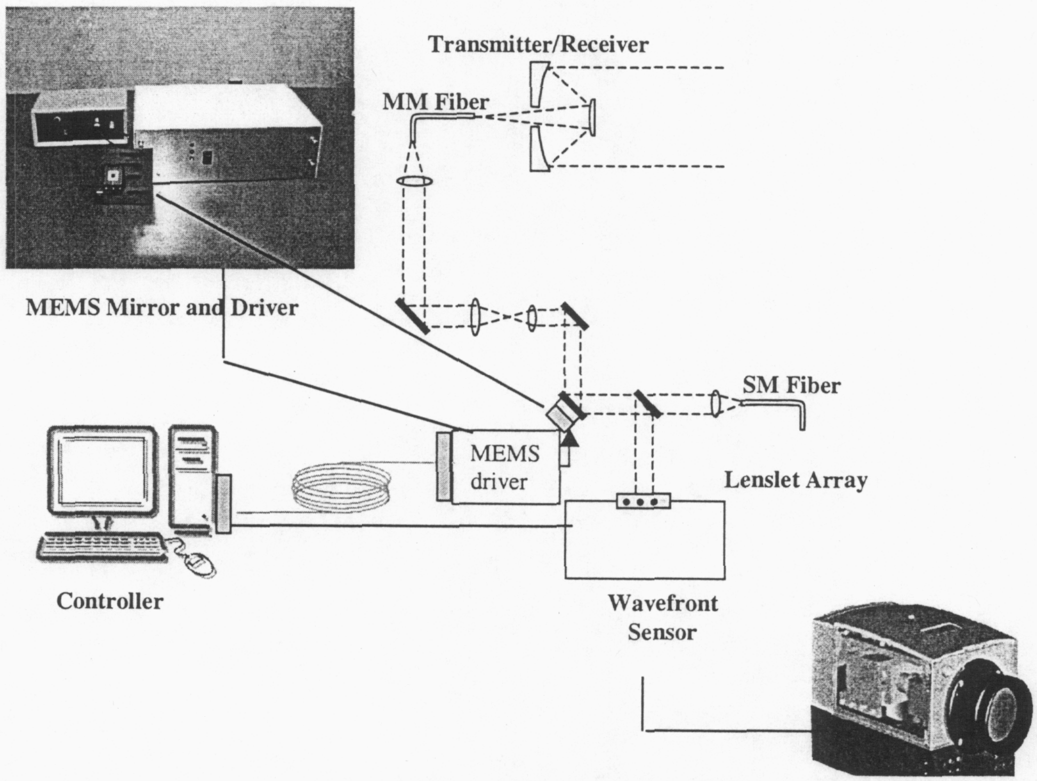

Figure 7. Schamatic of the proposed Adaptive Optics system. The camera is the Indigo Phoenix DAS and the MEMS is the Boston Micromachines 140 actuator device.

ACKNOWLEDGEMENTS

The work described in this report was funded through the Secure Air-Optic Transport and Routing (SATRN) Program an LLNL Directed Research and Development Strategic Initiative.

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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